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A review on cool thermal storage technologies and operating strategies

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ABSTRACT

The thermal energy storage (TES) system for building cooling applications is a promising technology that is continuously improving. The TES system can balance the energy demand between the peak (daytimes) and off-peak hours (nights). The cool-energy is usually stored in the form of ice, phase change materials, chilled water or eutectic solution during the nighttimes and used in the daytime. A well-designed TES system would effectively decrease the electricity demand with a reasonable cost. This paper summarizes the findings, investigations and analysis of the TES systems for the space cooling applications. In this regards, different types of storage technologies, as well as various operating strategies, are discussed and some of the outstanding case studies are presented. Since the TES system can provide any portion of the required cooling load, the designer must focus on the best practical and economical solution, which is mainly influenced by localized parameters. It is evident that to improve the available designing standard, a sustainable investigation on localized parameters such as the electricity demand trend, the peak and off-peak hours, the climate change profiles, the electricity tariff rate and the system setup costs are still required.

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1. Introduction

Before 19th century as there was no mechanical refrigeration system, any artificially cooling would be possible by using natural phenomena like ice, snow, underground cold water or natural evaporating cooling [1]. Nowadays, as the cool generator systems are becoming more developed, the existence of the storage devices is unavoidable. Generally, Thermal Energy Storage (TES) systems help reserving the energy in thermal reservoirs for later usage. They are designed to store either the higher (heat) or the lower (cold) temperature in comparison with the environment [2]. The energy might be charged, stored and discharged daily, weekly, yearly or in the seasonal cycles [3].

The cool energy is usually stored in the form of ice, chilled water, phase change materials or eutectic solution during the low

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Nomenclature

AC	air conditioning
AHU	Air Handling Unit
ARI	Air-Conditioning and Refrigerating Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFC	chloro-fluoro-carbons
COP	coefficient of performance
CWS	chilled water storage
DB	dry bulb
DE	district energy
gal	Gallon
h_{fg}	latent heat of fusion
HVAC	heating, ventilating and air conditioning
ITS	ice thermal storage
KMUTNB	King Mongkut's University of Technology, North Bangkok
kWe	kilo Watt electrical
kWt	kilo Watt thermal
MVF	molten volume fraction
MWe	megawatt electrical
MWt	mega watt thermal
n-$C_{18}H_{38}$	n-octadecane
PCM	phase change material
RT	Refrigeration tone
T_a	ambient temperature
TES	thermal energy storage
TMY	typical meteorological year
TRNSYS	transient systems simulation software

electricity demand hours [4,5]. The heat TES system frequently stores the collected heat from solar collectors in the packed beds, steam storage tanks or solar ponds to be used later in the domestic hot water process or for electricity generation applications [6–8]. The TES systems can be employed to balance the energy demand between the peak and off-peak hours (normally days and nights). There are also small but growing numbers of seasonal TES systems that store the summer heat for the purpose of space heating during the winter and store the winter cool for summer cooling. They have been perused in previous studies and have been found as a practical application [9–12].

2. Cool thermal storage system

Reserving cool thermal energy for later use is not a new concept, during the past century people harvest ice from the natural ice caves or from frozen rivers to keep themselves cold during summer or to preserve their stored food. The primary benefit of employing cool TES systems is to shift the power consumption from the peak to the off-peak periods, especially in cases when electricity is used, thus they are often named as "off-peak cooling" systems. Besides, due to the constant and comparatively lower temperature during the nights, usually they would consume less operating energy compared to the conventional air conditioning (AC) systems. It is important to know that reserving cool is significantly cheaper than storing electric power to make cooling [13]. Based on the report of the California Energy Commission [14], producing off-peak electricity would consume less fuel that makes it cheaper.

Many applications of cool thermal storage systems have been employed in the industry. Many of them have focused on different technologies and strategies to store the cool-energy for building applications by using thermal reservoirs or by pre-cooling control systems [15]. Another well-known application of cool TES systems is the preservation and shipment of temperature sensitive materials [16,17].

A comprehensive review paper on cool thermal storage technologies has been presented by Hasnain [18] in 1998. He demonstrates the advantages and disadvantages of the cool TES system over the conventional AC systems. Normally, these systems shift the electricity consumption from the daytimes to the nights when the ambient temperature (T_a) is considerably lower. It would consequently, improve the chillers' efficiency [19]. In addition, the constant cooling generation ensures efficient operating for the plant. The significant air temperature difference across the Air Handling Unit (AHU) also reduces the required circulated air volume. Therefore, smaller AHUs, less duct working and less electrical equipments are required. Moreover, as the chillers' capacity reduces, fewer gas charge refrigerants are required, which can help decreasing the emission of harmful CFCs into the atmosphere. Conversely, as the chiller produces lower chilled water temperature its performance is reduced significantly.

The performance of a TES system is commonly described by its coefficient of performance (COP) that is described as the ratio of the net refrigerating divided by the input power. The COP of a system during peak and off-peak hours is defined from the chiller and compressor design. However, the actual operating performance of a system is assessed through a real time fieldwork study. For this purpose, the net cooling capacity and required energy should be recorded continuously by using a numerator and a denominator. The COP of a chiller operating with ITS system during the charging period decreases significantly because of the low-temperature of chilled water production (around $-5.0\,^{\circ}$C) compared to the conventional AC systems. In 1992, it was assumed that the COP of the chiller throughout the charging period is around 23% lower in comparison to the normal operation conditions [20]. However, the real percentage of the TES system completely depends on the system configuration, storage strategy and the localized parameters. Generally, TES systems are considered as cost effective techniques [21].

Cool thermal storage systems are generally categorized in three types, which are chilled water, ice storage and eutectic salt TES systems [18]. More details of each system are described herein. Between these techniques, the Chilled Water Storage (CWS) and the Ice Thermal Storage (ITS) systems are the most promising ones in case of the normal applications. Table 1 shows some of the main differences between these three cool storage systems.

It can be clearly observed from Table 1 that the ITS system has the advantages of larger storage volume in comparison with two other systems. However, as mentioned earlier the COP of the ITS system is much lower than other techniques. Thus for a proper selection, further investigations on localized parameters such as the electricity demand trend, the peak and off-peak hours, the climate change profile, the electricity tariff rate and the system setup costs are the key elements that varied place to place. To investigate different parameters that affect the performance of a cool TES system many case studies have been conducted around the world and the results have published in the open literature.

In the past decades, the use of cool storage systems has been widely developed in the commercial and industrial scales thus plenty of information relating to these systems and developed technologies are presented. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have tabulated the available processes into the handbook where different geometries are described [3]. Various manufacturers have used these geometries on their production line such as Baltimore Aircoil Company (Ice Chiller) [24], Ciat Co. (Cristopia) [25], Calmac Co. (Ice bank) [26], or Sedical Co. (Cryogel) [27].

The statistical study shows that in the early 1990s around 1500–2000 units of cool TES systems were employed in the United

Table 1
Primary features of cool storage systems [18].

	Chilled water	Ice storage	Eutectic salt
Specific heat (kJ/kg K)	4.19	2.04	–
Latent heat of fusion (kJ/kg) [22]	–	334	80–250
Chiller type	Standard water	Low temperature secondary coolant	Standard water
Chiller cost per kW ($)	57–85	57–142	57–85
Tank volume (m^3/kWh)	0.089–0.169	0.019–0.023	0.048
Storage installed cost per kWh ($)	8.5–28	14–20	28–43
Charging temperature (°C)	4–6	−6 to −3	4–6
Chiller charging efficiency (COP) [23]	5.0–6.0	2.7–4.0	5.0–6.0
Discharge temperature (°C)	1–4	1–3	9–10
Discharge fluid	Water	Secondary coolant	Water
Tank interface	Open tank	Closed system	Open tank
Maintenance	High	Medium	Medium

States. Most of them were installed in the office buildings, schools and hospitals. The results show that ITS systems had the largest proportion of around 80%–85% followed by the chilled water applications with 10%–15% and the rest 5% were eutectic salt systems [28].

Saudi Arabia is one of the countries that recently has employed plenty units of ITS systems. The available applications and their economic effects in that region have been represented in a work done by Hasnain et al. [29]. A list of various types of installed units has been presented, and it was found that the TES system could decrease around 30%–40% of the peak cooling-load demand and 10%–20% of the peak electrical demand [30]. In another work, Hasnain et al. [31] have forecasted the cool thermal storage utilization based on two scenarios. They found that their proposed partial ITS model could decrease the peak electrical load for the first and second scenarios by 15% and 23%, respectively.

In the following sections, different types of cool TES systems have been described in details and some of the available literatures have been discussed briefly.

3. Chilled water storage techniques

Employing chilled water to store cool thermal is a well-known strategy in many countries to save energy by shifting power consumption from the peak hours of the day to the nighttimes [32]. During the past decade, many different types of CWS designs were developed and employed in the field prior to the successful evolution of thermally stratified systems. Primarily designs were in the manner to avoid temperature mixing of chilled water with return water. However, they often require complex tank configurations or piping systems that are expensive and difficult to operate. The CWS systems currently in use can be classified as labyrinth, baffle, tank series, multiple tanks with an empty tank, membrane and thermally stratified systems. Some of them are schematically illustrated in Fig. 1.

In 1996, Sohn et al. [34] have presented a report of a 8517 m^3 CWS tank installed by the US Army. The system shifts more than 3 MWe of the electrical demand to the off-peak hours. Andrepont [35] has studied on a 10 years old District Energy (DE) system in Chicago. The system was considered as one of the largest units in the world with a peak discharge rate of 25 k tons and a storage duty of around 123 k ton-h. In another study, Sebzali and Rubini investigate the performance effects of using CWS systems on the conventional AC system performance based on Kuwait's climate [36]. They found that in that province the CWS system can approximately decrease the peak electrical load up to 100% and decrease around 33% of the nominal chiller size.

Osman et al. [37] have used a three dimensional numerical modeling to determine the correlation between the chilled water thermal stratification and the tank size. In a recent work, Boonnasa and Namprakai [38] have presented a methodology for determining the optimal capacity of the CWS tank. They have presented the results of their study for the King Mongkut's University of Technology North Bangkok (KMUTNB) and they pointed out that for a CWS system consisting of two chiller units (of 450 RT) operating continuously, a TES of 9413 RT-h and 5175 m^3 volume, was the most suitable combination. Based on these configurations over two times of the mechanical chiller capacity and around 31% of the peak demand could be reduced.

4. Ice thermal storage technique

Among all the available cool thermal storage systems, the use of ice due to its high latent heat of fusion (h_{sf} = 334 kJ/kg [22]) was considered as the most popular technique during the past decade, especially when the available space is limited. Employing the ice allows the greater part of the base load to be stored for further use [3]. Obviously, even though the storage volume is determined based on the used technology, it generally varies between 0.019 and 0.027 m^3/kWh [39]. Fig. 2 shows the configurations of ITS heat exchangers of four reputable manufacturers.

The Air-Conditioning and Refrigerating Institute (ARI) has established special standard [42] and guideline [43] for TES equipments that defines the classifications, tests and rating requirements, minimum data for published ratings, etc.

As the thermal energy in this technique is stored in the form of ice, thus the supplied chiller must be able to produce charging temperature in the range of −6 °C to −3 °C, which are considerably lower than the normal range of the conventional chillers. The heat transfer fluid that is used in the ITS system might be either a refrigerant or a secondary coolant. Due to the reliability and simplicity of this technique, it has been widely used in buildings that are mainly occupied during the working hours such as the store building [44], campus buildings [45], court-hall [46], hospitals [47,48], subway station [49], schools [50], churches and mosques [51]. In 1991, Landry and Noble [52] found that employing the ITS system would help to downsize the cooling generation devices such as pipes, ducts and AHUs and consequently would lead to lower the primary cost of the HVAC system. During the past decade various studies on the issue of energy storage in the form of ice have been presented and variety of cold TES systems had been built and studied [53,54]. Comprehensive reviews on the TES [55] and especially on the cold TES [56] have been presented based on the works done before the year 2003.

The ice formation profile during charging is one of the key challenges that could influence the system performance. It is believed that adding side fins on the surface of the tubes would improve the thermal resistance. The melting of n-octadecane (n-$C_{18}H_{38}$) around a finned tube has been first studied by Lacroix [57]. Zhang and Faghri [58] found that by using internal fins the performance of a system with low thermal conductivity fluid could be improved up to 15%. They also investigated a similar study for the systems with external radial finned tubes and they found that by increasing the fin's height the molten volume fraction (MVF)

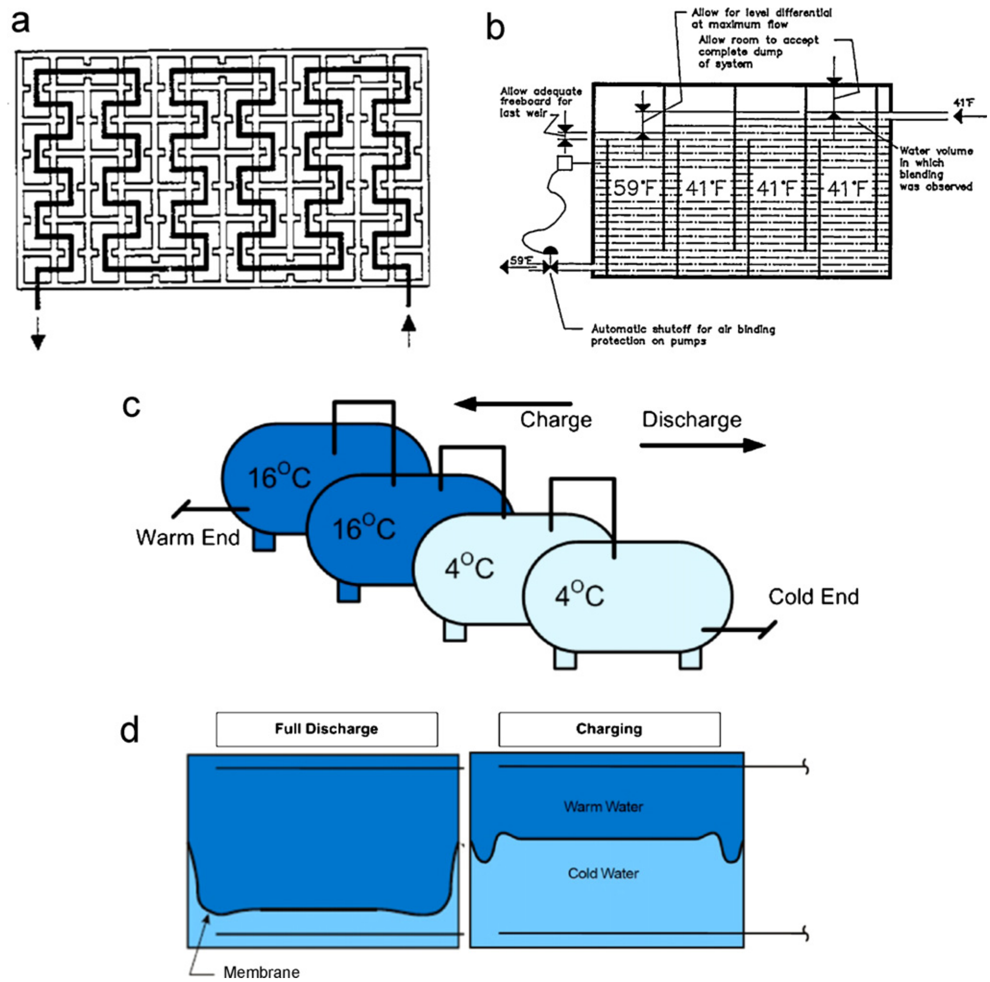

Fig. 1. (a) Labyrinth tank [32], (b) baffle tank [32], (c) series tank, and (d) membrane tank [33]. (The figures are used with the publisher permission.)

consequently increases [59]. In another work, Lacroix and Benmadda [60] presented the results of their study on the melting from a finned vertical wall. They found that as the fine numbers increase, the solidification rate improves. Ismail et al. [61,62] carried out parametric studies on solidification of PCM around a cylinder for storing ice. Teraoka et al. [63] investigated the characteristics of ice crystallization in a super-cooled solution. Kayansayan and Acar [64] performed an experimental study to investigate the temperature profile and the phase front distribution across the tube.

5. Different types of ITS systems

The ITS storage technologies are generally categorized by their different combinations of storage media, charging or discharging mechanism. Typically, an ITS system consists of a large tank of water or salt-water or small capsules of water or any material with solidification temperature lower than the available chilled water temperature of a building [65]. They are generally categorized into ice harvesting, ice-on-coil, ice slurry and encapsulated ITS systems [39]. In another point of view, they can be divided as either dynamic

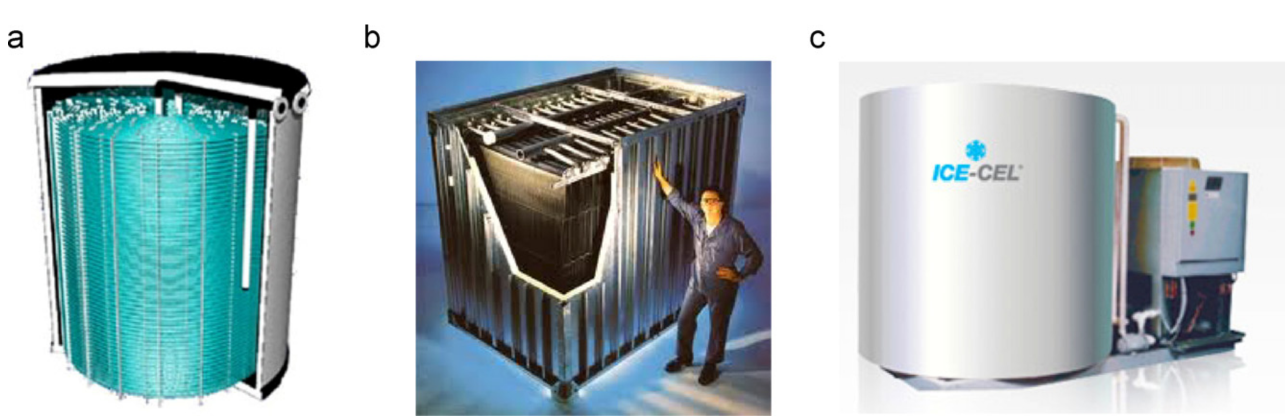

Fig. 2. ITS heat exchangers configuration: (a) Calmac [26], (b) Fafco [40] and (c) Dunham–Bush [41]. (The figures are used with the publisher permission.)

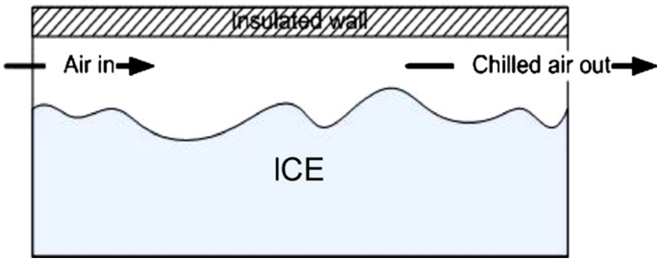

Fig. 3. Schematic diagram of a direct chilled air production system.

or static storage devises. In the static types, ice is formed directly on the chilling surface but in the dynamic types, the ice is formed and moved out of the cooling surface [66]. Henze et al. [67] performed a comprehensive study on two types of ice-on-coil and ice harvester systems to evaluate the bill saving effects of different strategies. In some recently proposed techniques, the air is cooled down by having a direct contact with the ice [68,69] (Fig. 3). Due to the lower thermal resistance, the heat transfer rate on the free surface increases. However, Clark [70] has mentioned in his report that although the ITS systems can successfully reduce energy costs, they cannot be clearly considered as green systems. Conversely, MacCracken [19] categorized the TES systems as green technologies due to their lower impact on the environment, which is the basic principle of being green.

5.1. Ice harvesters

The ice harvester system is classified as a dynamic type of ITS systems, which is usually consisted of an open insulated storage tank and a vertical plate surface positioned above the tank. During the charging period, the ice is formed on the plate's surface of the evaporator. A circulating pump brings the water at a temperature of 0 °C on the outer surface of the evaporator, which is fed internally with liquid refrigerant. Normally, thickness of the produced ice varies between 8 mm and 10 mm depending on the length of the freezing cycle. The ice would then be harvested by feeding a hot gas to the evaporator. The outer surface temperature rises to about 5 °C causing the ice in contact with the plates to melt and fall into the storage tank. During the discharging period, the chilled water that circulates through the storage tank, further reducing the water temperature to cope with the load [71]. An ice harvesting system diagram is illustrated in Fig. 4.

Knebel [72] has evaluated the system performance of an ice harvesting TES system with the aim of a simulation model. Ohira et al. [73] studied on the characteristics of ice melting in the ice harvesting system. They investigate the effects of the inlet water spraying method, the position of inlet water release and the water replacement time. They found that the characteristics of the ice melting in an actual tank could be evaluated by the average modified Stanton number. However, due to the system complexity, only a few manufacturers are involved with these systems, which are normally employed only in special applications.

5.2. Ice slurry

In this technique, the ice is formed by passing a weak glycol/water solution through the pipes submerged in an evaporating refrigerant. Fig. 5 illustrates a schematic drawing of the ice slurry system. The evaporating refrigerant would cool the solution and produce a suspension of ice crystals. The small ice particles are pumped or dropped directly into the storing tank. During the discharging process, the cool solution circulates from the tank either directly or indirectly through the AHUs [74–76]. Kitanovski and Poredoš [77] studied on the viscosity and concentration scattering of ice slurry in heterogeneous flow. Bellas et al. [78] investigated the pressure drop and heat transfer behavior of the ice slurry system. They found that by increasing the ice-fractions from 0% to 20% the pressure drop increases around 15%. They also found that the heat transfer capacity of the heat exchanger with melting the ice slurry is around 30% more than conventional chilled water flow systems. In another survey, Yamada et al. [79] proposed the oscillatory rotating cooled tube as a production method of the ice slurry. Egolf and Kauffeld [80] conducted their work on physical properties of ice slurries and they found that if the ice fraction maintained below 15%–20% the fluid would have the Newtonian fluid behavior.

5.3. Encapsulated ice

An encapsulated ice storage system consists of numbers of spheres or rectangular plastic capsules of water immersed in a secondary coolant such as ethylene glycol in a steel or concrete tank. In the United States, rectangular containers of approximately

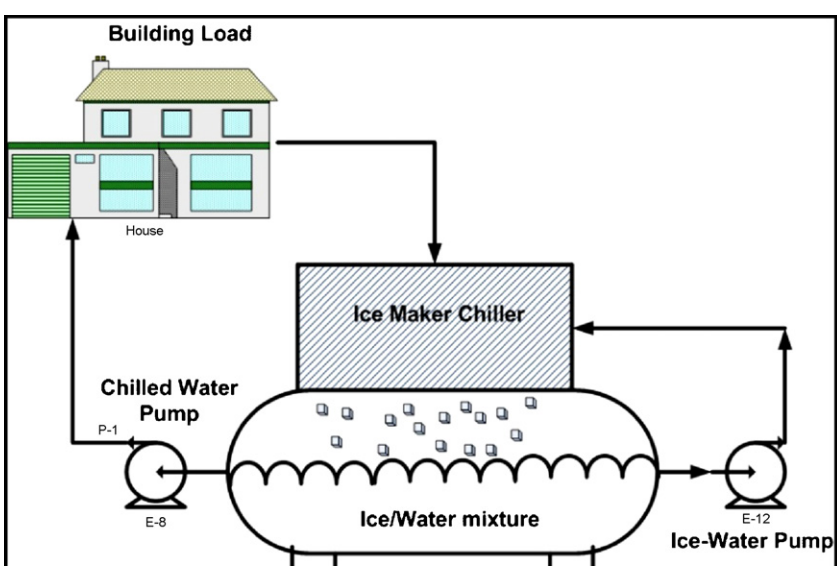

Fig. 4. Schematic diagram of a typical ice harvesting ITS system.

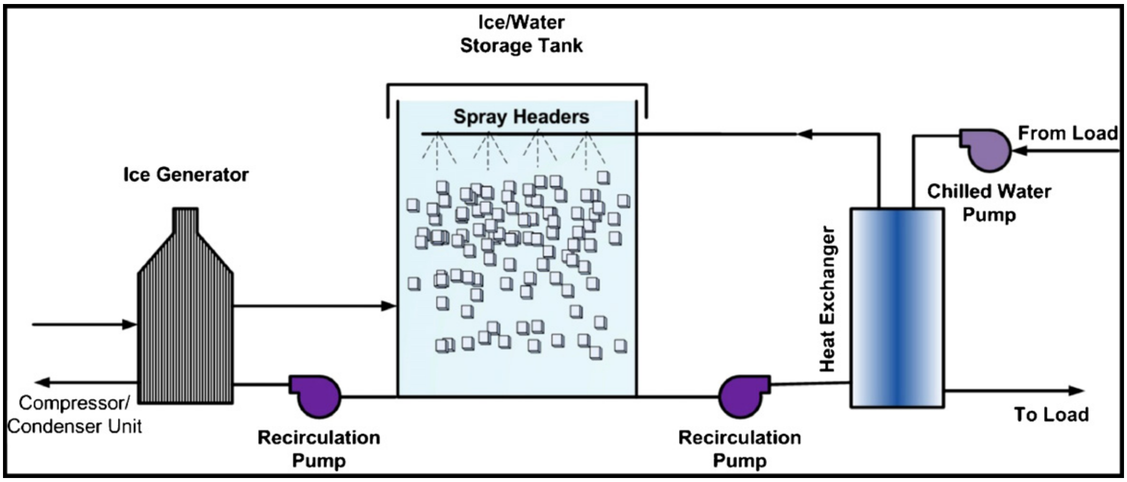

Fig. 5. Schematic diagram of an ice slurry storage system.

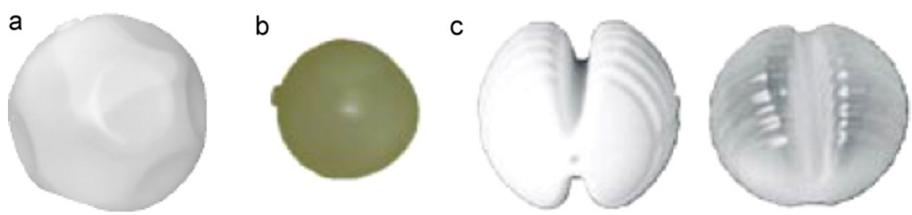

Fig. 6. Samples of encapsulated ice containers: (a) Cryogel [84], (b) Crystopia [33], and (c) Ice-Bon [33]. (The figures are used with the publisher permission.)

0.017 m^3 and 0.0042 m^3 size and dimpled spheres of 100 mm diameter capsules are available. However, in Europe, spheres of 95 mm and 75 mm diameters are utilized [39] (see Fig. 6). The capsules are usually made of a high-density polyethylene that is able to bear up the pressure due to the water expansion. During the charging period, a low temperature solution (−6 °C to −3 °C) passes through the tank and freezes the water inside the capsules. In the discharging period, the warm solution returns from the load to the tank and melts the ice. Fig. 7 shows the charging and discharging procedure of the encapsulated ITS system [81,82]. Saitoh and Hirose [83] performed an experimental and numerical investigation to evaluate the thermal specifications of the encapsulated thermal storage tank. They indicate that the size and material of the capsule as well as coolant temperature and flow rate are the main parameters that determine the charging and discharging duration.

There is a special kind of paraffin that can be used in the spherical capsule as its melting temperature is higher than water but has the same latent-heat capacity with the average heat transfer coefficient of around 40% higher than water [85]. Regin et al. [86] presented a complete review on heat transfer characteristics of the TES system utilizing the PCM capsules. In a recent work Bédécarrats et al. [87] performed an experimental study to investigate the charging and discharging performance of the encapsulated ITS system.

Chen et al. [88] carried out an experimental investigation on both the pressure drop and the thermal performance during the charging process of an encapsulated thermal storage tank. They indicate that by decreasing the inlet coolant temperature and increasing its flow rate, the efficiency of the storage tank improves. Eames and Adref [89] performed an experimental study to investigate the phases changing processes (freezing and melting) in spherical capsules. They proposed a semi empirical equation to predict the mass of ice, which is formed in a sphere during the charging and discharging period. The optimum charging mode was captured in the vertical arrangement as the natural and forced convections were in a same direction [90].

5.4. External melt ice-on-coil storage systems

The external melt ice-on-coil TES system is sometimes referred to the ice builder because in this storage system the ice is formed on the outer surface of the heat exchanger coils submerged in an insulated open tank of water as shown in Fig. 8 [91,92]. During the charging procedure, a liquid refrigerant or a glycol solution circulates inside the heat exchanger coils and produces ice on the outer surface of the coil. The ice thickness is usually

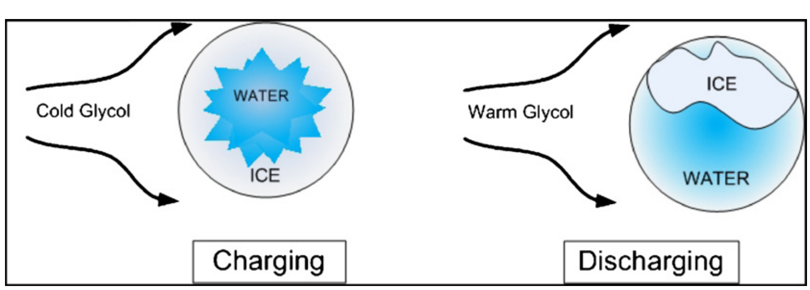

Fig. 7. Charging and discharging procedure of an encapsulate ice storage.

Fig. 8. A photograph of an external melt ice-on-coil system (sub-systems of an Ice-Bear® unit) [94].

varied between 40 mm and 65 mm depending on the application. The thinner layer is suitable where higher charging temperatures (−7 °C to −3 °C) is required and thicker layer is used for applications where lower charging temperatures (−12 °C to −9 °C) is required. During the discharging process, the returned water from the load circulates while passing through the ice tank and cooled down by direct contact with the ice [93]. The charging and discharging processes of the external melt ice-on-coil is illustrated in Fig. 9.

Soltan and Ardehali [95] numerically simulated an ice-on-coil TES system to determine the approximate duration of water solidification around a circular cross-section coil. They found that it takes approximately 2600s to form 10 mm of ice around a pipe of 20 mm diameter.

5.5. Internal melt ice-on-coil storage systems

In the internal melt ice-on-coil storage systems the heat transfer fluid such as the glycol solution circulates through winding coils submerged in tanks filled with water. During charging, the low temperature glycol solution (−6 °C to −3 °C) flows through the coils inside the tank and produces ice on the coil's outside surface. During the discharging process, the warm glycol solution flows through the coils causing ice to melt from the inside out [96]. Silvetti [97] provided the fundamental methodology for sizing an internal melt system. Fig. 10 shows the schematic charging and discharging processes of an internal ice-on-coil storage system.

6. Operation strategies of cool TES systems

The Cool TES system strategies are generally classified in two major divisions of full or partial storages indicating the sum of shifted cooling load from the peak to the off-peak periods. The partial storage strategy could be further categorized as chiller priority or storage priority types. It should be mentioned that the relationships between the electric rate structure, building load profile and the costs of equipment and storage are critical in determining the most cost effective mode of operation.

6.1. Full storage strategy

In the full storage strategy, all the required building loads will be transferred from the peak to the off-peak periods (usually from days to the night times). Thus, the chiller operates at its maximum capacity when the cooling load is at the minimum and charges the storage tanks. Since the full storage strategy provides the whole demand load during the off-peak periods, thereby, in comparison to the partial storage strategy, the chiller size is significantly higher and is approximately equal to the non-storage condition. This strategy is suitable for conditions that the peak load occurred in a short period or there are small overlaps between peak energy hours and peak loads [98].

6.2. Partial storage strategy

In the partial storage strategy, chillers will supply part of the demand cooling load while the stored cooling provides the rest, thus the chiller size is usually smaller than the design load. This is an interesting approach for many designers as there are numbers of successful designs with a total cost of equal or even less than the non-storage conventional AC system.

This strategy is further categorized based on the selected operation strategies as the load leveling (the chillers operate at full load for 24 h and the storage provides the extra required cooling) or demand limiting operations (the chiller operation is controlled during the daytime in order to keep the electricity cost as low as possible). The load leveling strategy is proper for cases that the maximum load is significantly more than the average load. However, in this strategy the electricity demand reduction is less than the full storage strategy. Fig. 11 shows the difference of just mentioned strategies. Table 2 illustrates how the different storage strategies could affect the performance of a sample CWS system [32].

The chiller priority or storage priority is another way of categorizing the partial storage strategies. In the just mentioned operating

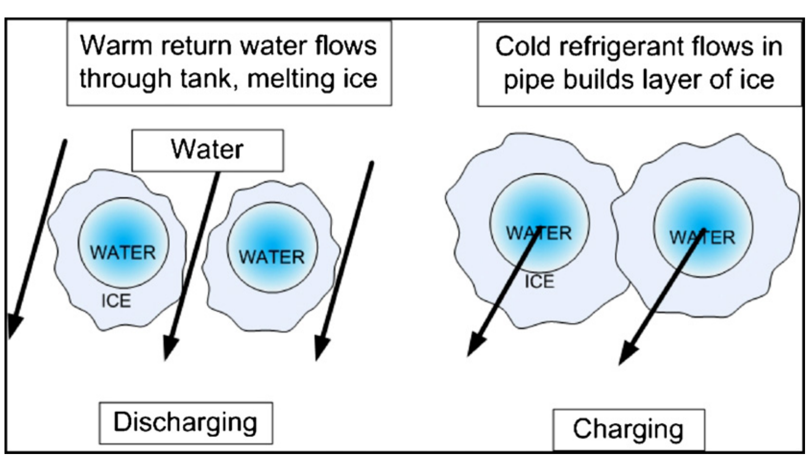

Fig. 9. The charging and discharging procedure of an external melt ice storage system [3].

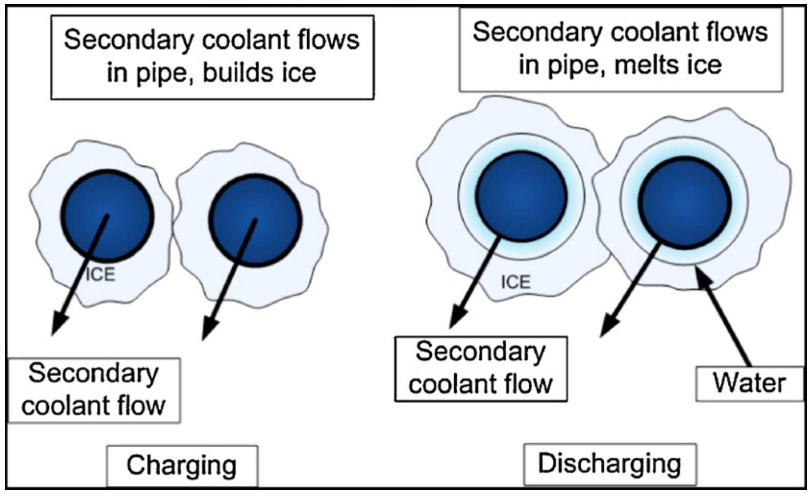

Fig. 10. Charging and discharging procedure of an internal ice-on-coil storage system [3].

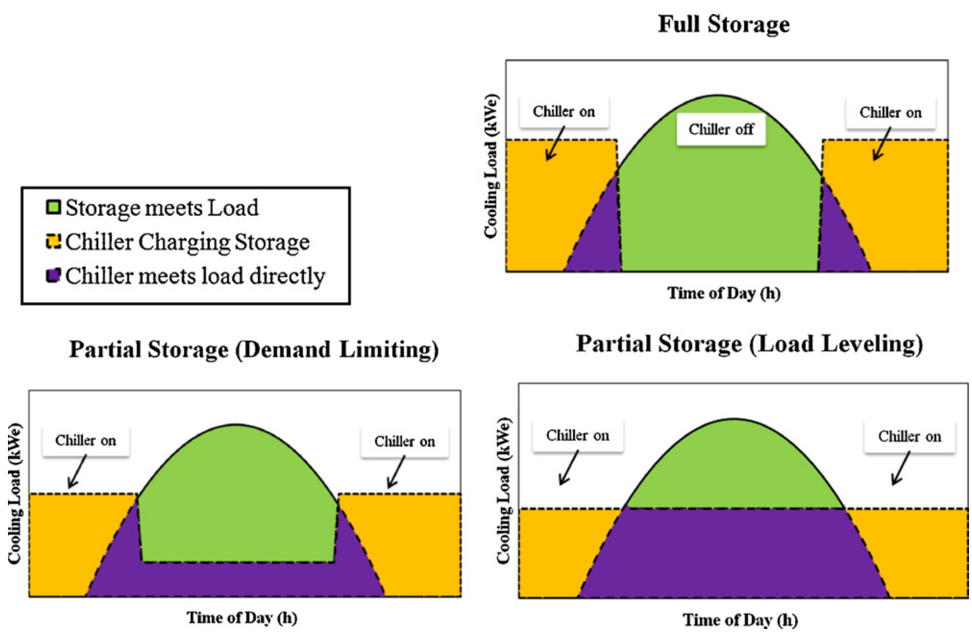

Fig. 11. Comparison of different operating strategies of cool thermal storage system [39].

strategies, either the chillers or the storage system provides the required building cooling load. The main difference between the storage and chiller priority strategies is the device that supplies the main proportion load, which is storage tank and chiller, respectively. Generally, the storage size and the chillers' capacity in the storage priority strategy are larger with more complex control, which helps them to consume lower energy [99].

Table 2
The effects of different storage strategies on a sample CWS system during a peak day [32].

System	Chiller size (tons)	Storage (ton-h)	Chiller – on peak	
			kW	kWh
No storage	120	0	96	960
Full storage	90	1200	0	0
Partial storage (demand limited)	70	980	0	220
Partial storage (load leveling)	50	700	40	400

7. Case studies

Office building, Dallas, TX, USA, 1989: An internal ice-on-coil storage system was installed in an office building located in Dallas, in order to shift about 800 kWe electric demands from the daytime to the night time and to save an estimated of US $55,000 per annum [100]. For this purpose, different cooling strategies have been studied and it was found that by using the load leveling partial storage strategy, smaller chiller and storage system are required in comparison with the full storage strategy. The study on the demand limiting partial storage strategy shows that the size of the chiller and storage system was fallen somewhere between those of full storage strategy and load leveling partial storage. Tackett [100] reports that the system has a payback period of 0.34 years for the load leveling partial storage, 2.35 years for the demand limiting partial storage and 1.34 years for the full storage strategy systems.

Dental clinic, TX, USA, 1991: In 1991, the ice harvester TES system was installed in a dental clinic at Fort Bliss, TX [101]. The design cooling load of the building varied from 197 kWt (from 12:00 to

Fig. 12. The 2.25 Mgal chilled water storage tank installed at Fort Jackson, SC [102].

13:00) to 204 kWt (from 15:00 to 16:00). The ice harvester system consists of a 91.4 kWt icemaker and 1.1 MWt steel storage tank. The ice harvesting system operates from 20:00 to 5:00 while all the AHUs were shut down and during this period, the building was not cooled. The system was shut down from 5:00 to 12:00 and the existing conventional chillers were switched on to directly cool the building. From 12:00 to 16:00, the chillers were switched off and the building cooling was met only by the stored ice. Finally, from 16:00 to 20:00 the chillers were switched on again and directly cool the building. The ice harvester system shifted the electric power consumption to the off-peak hours. However, the use of the ice harvester system consumes about 29% more electrical energy than the conventional AC system.

Department store, Oxford Street, London, 1994: An external melt ice-on-coil storage system was installed in a store in Oxford Street, London [44]. The system was designed to supply half of the required building load of a day design. The system was operated based on the storage priority control strategy, thus there was no need to increase the chiller size. The existing AC system was consisted of three screw chillers providing 3.0 °C chilled water during the daytime (603 kWt) and −6.0 °C during the night time (450 kWt). The ITS system provides around 9.3 MWt of cooling during discharging period. The chillers were designed to start charging the storage tank in 10 h starting at 9:00. During the discharging cycle, the stored ice provides the required cooling load as much as possible and the remaining load was supplied by the chiller. For days closer to the design day conditions with a peak load of 2.6 MWt and total integrated load of 17.4 MWt, the discharging cycle starts at 9:00 and finished at 17:00. The stored ice provides about 9.2 MWt of the base cooling load and the rest of 8.2 MWt was handled by chillers. The results of this case study show that the ITS system has significantly reduced the ongoing charges by shifting part of the demand electricity load to the off-peak hours.

Fort Jackson, 1996: In 1996 an investigation has been conducted in Fort Jackson, US, to design, construct and operate a massive CWS system [102]. A large capacity (2.25 Mgal) CWS system has been constructed that could serve more than half of the Fort Jackson's cooling load. The reported results of a two-year operation show that the system could save annually around $0.43 M of electrical utility cost for Fort Jackson. Fig. 12 shows the installed chilled water storage tank in Fort Jackson, SC.

Typical office building, Thailand, 2001: Chaichana et al. [103] presented the results of their case study on a typical office building in Thailand. An internal ice-on-coil ITS system was simulated based on the model presented by Neto and Krarti [104]. The results show that under the Thailand's electricity tariff rates the full storage strategy is able to save up to 55% of the required cooling electricity cost monthly. It was also found that by using this strategy the total energy consumption reduces around 5%.

A clinic building, Kuwait, 2005: Due to the hot climates, considerably long summer and low energy costs in Kuwait, the AC systems consume around 61% of the peak electrical duty and around 40% of the total electricity consumption. Sebzali and Rubini [105] conducted their case study on a clinic building. They examined different storage strategies through a computational modeling. They found that incorporating full storage strategy results to the highest electricity reduction for the selected building, but the size of the required chiller and storage system are higher in comparison to the other operation strategies. They show that by transferring the charging periods from 18:00 to 20:00 the total energy usage can be reduced due to the benefit of the lower Dry Bulb (DB) temperature. The full storage operation strategy requires larger chiller and higher storage capacity while the partial storage strategy (load leveling) requires smaller chiller and storage capacities.

Mosque of Makkah, Saudi Arabia, 2007: Habeebullah [51] conducted an investigation on economic feasibility of using the ITS systems in the AC plant in the Mosque of Makkah. The results indicate that as the existing electricity rate is fixed (0.07 $/kWh), the ITS system does not have any gain neither for the partial nor for the full storage strategy. However, the author found that by employing the energy storage system via full load storage strategy combined with an incentive time structured rate, the electricity cost could be reduced significantly.

Fossil Ridge High School, Southeast Fort Collins, 2008: The innovative design for the school building has won multiple awards; the AC system is cost effective and provides an exceptional environment for occupants [106]. The system consists of a 135-ton chiller and the partial ITS system combines with an interactive direct digital control system that manages all the equipments to maintain a comfortable environment. The school consumed around $100,000 less in energy costs between the years 2004–2005 in comparison with its sister school.

Elementary school, CO, 2010: Morgan and Krarti [107] presented the results of their field survey on an elementary school with total floor area of 65,000 ft^2 in two levels (48,000 ft^2 on the ground level and 17,500 ft^2 on 2nd floor). They investigated the influences of using active and passive TES systems to shift the peak cooling loads to the nights and reduce building energy costs. The set point temperature during the occupied periods (8:30–17:00) was 24 °C and it was 32 °C during unoccupied periods. A 50 ton scroll compressor operates during the night (from 2:00 to 8:00) and charges three ice-tanks with a total capacity of 570 tons/h using the internal melt ice-on-coil system. In the discharging period, the chiller was kept in assist mode to handle any unexpected cooling loads. They found that around 47% of the annual electricity cost could be saved by employing the TES systems. This huge cost saving is due to the incentive utility rate of $0.0164/kWh as a flat consumption rate and a demand charge of $11.24/kW.

Library building, Malaysia, 2010: A recent simulation case study was conducted in a typical library building situated in the tropics by Yau and Lee [108]. They used a Typical Meteorological Year (TMY) weather profile of Kuala Lumpur with the aim of the Transient Systems Simulation Program (TRNSYS) software. They employed the ice-slurry cooling storage system in their simulation and they found that by employing the ITS system with the full storage strategy, the cumulative energy consumption would be increased by 20% due to the higher chiller energy consumption and the longer water pump usage compare to the baseline design. However, with considering the electricity tariff rate of Malaysia, using the ITS system would reduce the bill costs around 24%.

8. Concluding remarks

A literature review has been carried out to investigate different types of the cool thermal storage systems; in this regards some of the various available cases have been briefly described and some of the basic technologies have been discussed. The literature review reveals the advantages and disadvantages of different types of the TES techniques and the storage strategies. However, due to the simplifications and approximations made by the authors, not all of the presented results could provide accurate guidance.

A comparison study between the available systems shows that the ITS system has the advantages of larger storage volume capability, but it has a comparatively lower COP than other available techniques. Therefore, in order to choose the best TES system further investigations based on the local situation are highly recommended. The localized parameters have to be carried out through various case studies in different countries with different climates, cultures and energy policies. The important local parameters that should be derived out are the electricity demand trend, the peak and off-peak hours, the electricity tariff rate, the system setup costs, and the energy policy.

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